Development of a Calibration Rig for a Large Multi-Component Rotor Balance

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Abstract

A calibration rig has been designed and constructed at the NASA Ames Research Center to calibrate the multi-component rotor balance in the Large Rotor Test Apparatus. The rotor balance capacity is 52,000 lbs thrust, 15,000 lbs shear force, and 125,000 ft-lbs of roll and pitch moment. The rotor shaft flex-coupling has a torque capacity of 164,800 ft-lbs. Eleven hydraulic actuators with in-line load cells, operating in a tension mode only, are used to apply the calibration loading. The Large Rotor Test Apparatus, the rotor balance, and the design and operation of the calibration rig are described.

Introduction

The Large Rotor Test Apparatus (LRTA) is being developed at the NASA Ames Research Center (fig. 1). The LRTA will be used for the testing of large, full-scale rotor systems up to 52,000 pounds of thrust in the 40-by-80- and 80-by-120-Foot Wind Tunnels. A five-component balance is installed in the LRTA to measure the rotor forces and moments. An instrumented shaft-flex-coupling measures the rotor torque.

The NASA Ames Research Center also operates the smaller Rotor Test Apparatus (RTA) for the testing of medium, full-scale rotor systems up to 25,000 lbs of thrust. The RTA is similarly equipped with a five-component balance and an instrumented shaft-flex-coupling for the measurement of the rotor forces and moments. Experience with the RTA showed the necessity of performing an installed balance calibration to obtain the desired accuracy of balance load measurements of 0.5% of component capacity or better. A calibration rig was therefore developed at NASA Ames Research Center to allow for the calibration of the multi-component balance while installed in the LRTA.

This paper first presents the major features of the LRTA and its multi-component balance. The major components of the calibration rig are the calibration frame, the calibration body, the hydraulic actuator load system, and the data acquisition system. The design criteria for and the mechanical design of the calibration frame are discussed followed by a description of the calibration body. Subsequently the hydraulic actuator load system and its operation are described. Finally, the data acquisition system and the data reduction program are discussed.

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14. ABSTRACT
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Figure 1: Large Rotor Test Apparatus

Large Rotor Test Apparatus Description

To enable moderate-to-large helicopter rotor system testing in the National Full-Scale Aerodynamics Complex (NFAC), NASA and the U.S. Army have recently completed the development of a new research test capability. The Large Rotor Test Apparatus (LRTA), designed and built by Dynamic Engineering, Inc., is a special-purpose drive and support system for operating helicopter rotors up to 52,000 lbs thrust.

The LRTA is a relatively large structure compared to present test stands for wind tunnel tests of rotors. The exterior configuration of the fuselage is basically a body of revolution with an overall length of 480 inches and a maximum diameter of 100-inches (fig. 2). The LRTA is designed to be supported by three wind tunnel support struts, two forward and one aft.

Contained within the external fairing structure is a frame designated the main support chassis which is supported by direct connections to the three struts. The chassis provides the base to which the following are directly attached: a transmission, two electric drive motors, which engage the transmission symmetrically from opposite sides, and the fuselage fairing structure. Connection of the fairing structure to the chassis is effected by a statically determinant arrangement of six load cells. These load cells allow determination of the steady aerodynamic forces and moments on the fairing structure.

Seated on top of the transmission case is the rotor balance. The function of the rotor balance is to enable measurement of the rotor hub forces and moments. The balance is described in the next section.

The upper output unit is the final element in the transfer of power from the transmission to the rotor system. It supports the rotor and transfers rotor forces to the rotor balance. The upper unit consists of a universal output shaft, upper and lower bearings, a flexible coupling adapter, and an upper output housing.

The output shaft has two distinct sections. The first section is contained inside the upper housing and is designed to withstand all combinations of LRTA design loads. The second section extends up to the rotor hub and is designed to be replaceable. This second section is normally designed to mate with an existing rotor system and, as such, may have significantly less load-carrying capability than the rest of the LRTA.

The lower end of the rotor shaft connects to the instrumented flexible coupling which, in turn, connects to the transmission. This flexible coupling is instrumented to measure rotor torque as well as residual thrust.

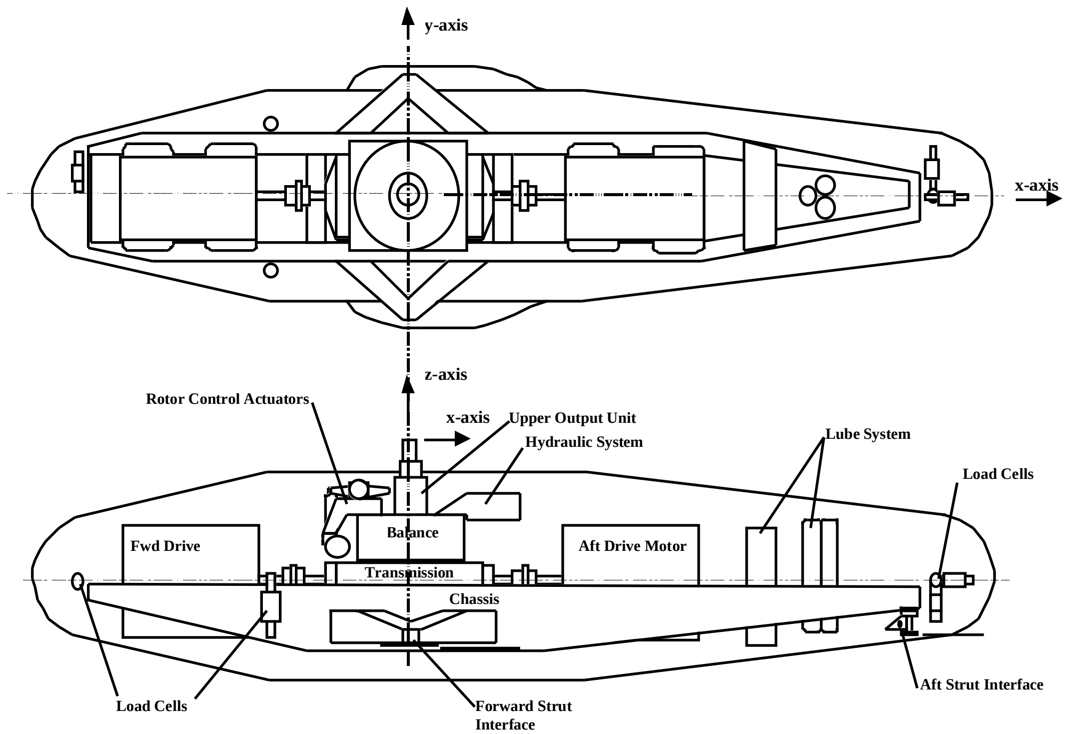


Figure 2: Schematic of the Large Rotor Test Apparatus

Rotor Balance Description

The LRTA rotor balance is installed onto the LRTA transmission (non-metric side) and supports the shaft's upper-housing (metric-side). The rotor shaft runs through the center of the balance and the rotor forces and moments (except shaft torque) are transferred to the upper-housing by thrust and radial bearings. The LRTA shaft has an in-line flex-coupling which is instrumented to measure the shaft torque and the residual thrust along the rotor shaft. The design, load-capacity, and gaging of the balance and flex-coupling are described in this section.

<u>Balance physical description:</u> The rotor balance is a one-piece balance made of a 15-5 PH stainless steel custom forging in the form of a ring. Cutouts were made in the vertical center of the ring to leave four symmetrically placed, rectangular flexure posts, connecting the metric and non-metric ring structure (fig. 3). The flexure posts measure 1.4-by-1.4-inches in cross section, are 2.85 inches tall, and are located at 90 deg intervals around a 44-inch diameter circle. These posts are designed and gaged to measure five components of forces and moments. These include normal, axial and side forces, together with rotor pitch and roll moments to rotor thrust levels of 52,000 lb. The sixth component, rotor torque, is measured by an instrumented flexible coupling mounted between the transmission and the rotor output shaft. The flexure post design was optimized for stiffness to eliminate balance resonance in the operating range of the mounted rotors and to provide strain levels adequate for accurate measurement. Temperature stability is provided by circulating cooling water through passages above and below the flexure posts on

both the inside and outside of the balance ring. These passages provide sufficient heat transfer to provide stabilized temperatures within 2 deg F of the cooling water. Polyurethane foam encasing the perimeter of the rotor balance provides thermal insulation from the surrounding environment.

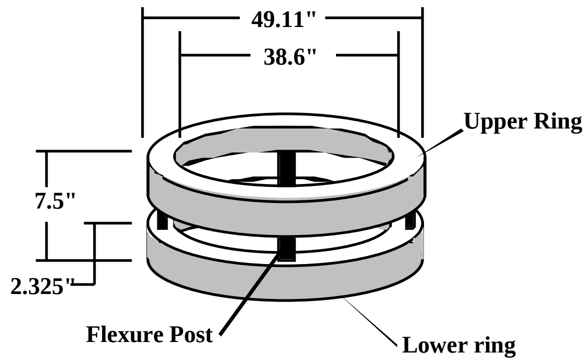


Fig. 3: Schematic of rotor balance

Flex-coupling physical description: The flex-coupling consists of a non-metric and a metric flange interconnected by a torque tube. The metric flange is located above the transmission, the torque tube extends through the middle of the transmission, and the non-metric flange is located below the transmission. The non-metric flange is secured to the transmission output shaft flange.

Balance gaging: The four flexure posts are identified by their location around the balance circumference. As seen from a LRTA's pilot perspective, the flexures are at 0 deg azimuth (aft), 90 deg azimuth (to the right), 180 deg azimuth (forward), and at 270 azimuth (to the left). Each flexure post is instrumented with three four-arm-active Wheatstone bridges, measuring the three mutual perpendicular forces with respect to the flexure. Micro Measurement 5,000 Ohm strain gages designed for a bridge excitation voltage of 20 VDC are used in the Wheatstone bridges. Back-up Wheatstone bridges are installed as well providing a total of twenty-four bridge readings for the rotor balance. The two groups of twelve bridge readings are referred to as the primary and secondary gage sets.

The availability of bridge readings, representing three mutual perpendicular flexure forces allows for the estimation of the maximum stress level the flexure sees under multi-component balance loading. This allows for monitoring of balance health by monitoring the flexure stresses rather than monitoring the balance forces and moments. During wind tunnel testing, the bridge responses are input to online data reduction software to estimate maximum peak stress and oscillatory stress, which are combined to determine the effective stress relative to a Goodman diagram for the balance material. The effective stress level for each balance flexure is monitored during the test to ensure that the balance is operated safely without using up fatigue life. This type of balance health monitoring has been found to be much more efficient than monitoring the mean and oscillatory loading of the balance forces and moments.

Note that the described balance gaging does not provide direct measurements of the three forces and three moments. Rather, the twelve individual bridge readings per gage set (three bridge readings for four posts) are combined digitally in the data reduction software to obtain the equivalent three force and three moment readings for the rotor balance (see data acquisition system section).

Balance temperatures: Twenty thermocouples are installed on the rotor balance to monitor the temperature distribution around the balance. Thermocouples are located at the metric and non-metric ends of each flexure. Thermocouples are also placed on the non-metric and the metric ring, mid-way between the flexures. Four thermocouples are located at the 90 deg azimuth station to provide a temperature distribution in the vertical plane.

Flex-coupling gaging: Micro Measurement 5,000 Ohm strain gages designed for a bridge excitation voltage of 20 VDC are used in four arm-active Wheatstone bridges to measure flex-coupling torque and residual thrust. A primary and a secondary gage set are installed on the flex-coupling. The torque sensor gages are located on the torque tube, midway between the two flex-coupling flanges. The residual thrust gages are located on the metric flange of the flex-coupling.

Flex-coupling temperatures: Two temperature measurements from the flex-coupling are available; 100 Ohm film type RTDs are installed at the center plane of the flex-coupling torque tube. These RTDs are located next to the flex-coupling torque strain gages and the two RTDs are at a 90 deg azimuthal spacing. The RTDs are a three-wire gage system; each RTD is part of an external Wheatstone bridge and the RTD forms one leg in this bridge.

Balance/flex-coupling loading: The definition of the forces and moments for the LRTA and for the rotor balance/flex-coupling follows the standard wind tunnel load definition and is defined in table 1 (as seen from a pilot's perspective). Note that the forces and the pitch moment follow the right-hand rule, but that the roll and yaw moments do not. The LRTA rotor balance/flex-coupling load capacities are shown in table 1.

Initial calibration limits: The LRTA installed rotor shaft is selected for interfacing with an existing rotor system and because of shaft stress limits the actual allowable balance calibration loading is restricted to being below the balance capacity for several components as shown in table 1. The axial and side force calibration loading will be to 100% capacity. The initial calibration loading of normal force and pitch and roll moments will be to ~50% of load capacity. The flex-coupling torque component was calibrated separately and will check-loaded in the calibration rig to 50% of load capacity.

The rotor shaft will be replaced prior to planned future wind tunnels with a higher capacity shaft. The LRTA will at that time be re-installed into the calibration rig and the rotor balance will be calibrated at that time to the balance load capacities or to the limitations of that shaft.

Table 1: Balance force and moment definition and capacity

Component, id.	sign convention	capacity	calibration range
axial force, AF	positive aft	±15,000 lbs	±15,000 lbs
side force, SF	positive to the right	±15,000 lbs	±15,000 lbs
normal force, NF	positive upwards	-3,000 to 52,000 lbs	-3,000 to 25,000 lbs
roll moment, RM	positive right side down	±125,000 ft-lb	82,000 ft-lb
pitch moment, PM	positive nose up	±125,000 ft-lb	82,000 ft-lb
yaw moment, YM (residual torque)	positive right side aft	±1,000 ft-lb	
shaft torque, TQ	positive right side aft	±164,800 ft-lb	82,000 ft-lb
residual shaft thrust, TH	positive upwards	±330 lbs	±330 lbs

Requirement for Installed Balance Calibration and Calibration Rig

NASA Ames Research Center operates the smaller Rotor Test Apparatus (RTA), which is also equipped with a multi-component balance. A bench calibration of the RTA balance was performed. However, subsequent check loading of the balance after installation into the RTA showed substantially differences in balance load responses under similar loading between the bench calibration setup and the RTA installed configuration. These differences in load response were shown to be attributable to a difference in the load distribution among the various balance flexures as seen during the bench calibration and the RTA installed check loading. The bench calibration rig did not allow for adequately modeling the non-metric end-conditions of the balance installation in the RTA. An installed calibration was therefore performed for the RTA balance.

The experience with the RTA balance clearly points to the requirement to perform the calibration of the LRTA balance while installed into the LRTA. As the LRTA balance capacity greatly exceeded the RTA balance capacity, a new calibration rig has been developed.

The major components of the calibration rigs are: the calibration frame, the calibration body, the hydraulic actuator system, and the data acquisition system. This calibration frame is modular in design and can be adapted for performing installed calibrations of both the LRTA and RTA rotor balances. The frame supports the LRTA and provides a rigid support for the hydraulic load actuators. The calibration body provides the interface between the load actuators and the LRTA. A modular design was used for the calibration body to facilitating interfacing with different RTA and LRTA rotor shafts. The calibration rig's components are described next.

Balance Calibration Frame

The calibration frame consists of an open structural box constructed from I-beams. The frame's design criteria and mechanical design are discussed below.

<u>Design criteria</u>: The design criteria for the structural box was to minimize frame deflections when applying single- and multi-component loading to the rotor balance up to 100% of the balance capacity. The deflections of the box frame were computed using the MultiFrame4D v4.1 program from Formation Design Systems for the various single and combined load cases, which are to be applied to the balance. The structural beams, making up the open structural box, were sized such that the deflection of the load attachment point was minimal under the maximum balance loading to be applied.

<u>Design</u>: An open structural box of I-beams was designed around the LRTA to provide an attachment for the hydraulic load actuators (fig. 4). This structural box was sized to surround the LRTA with its access doors in the opened position to allow for access to the equipment within the LRTA so that model preparation work could proceed during the build up of the balance frame (fig. 4a). The opened access doors placed the structural beams, making up the vertical side walls of the open box, at approximately 100-inches from the balance moment center. A similar distance was used forward and aft of the LRTA to locate the remaining vertical sides of the open structural box (fig. 4b). Figure 5 shows the LRTA installed in the calibration rig.

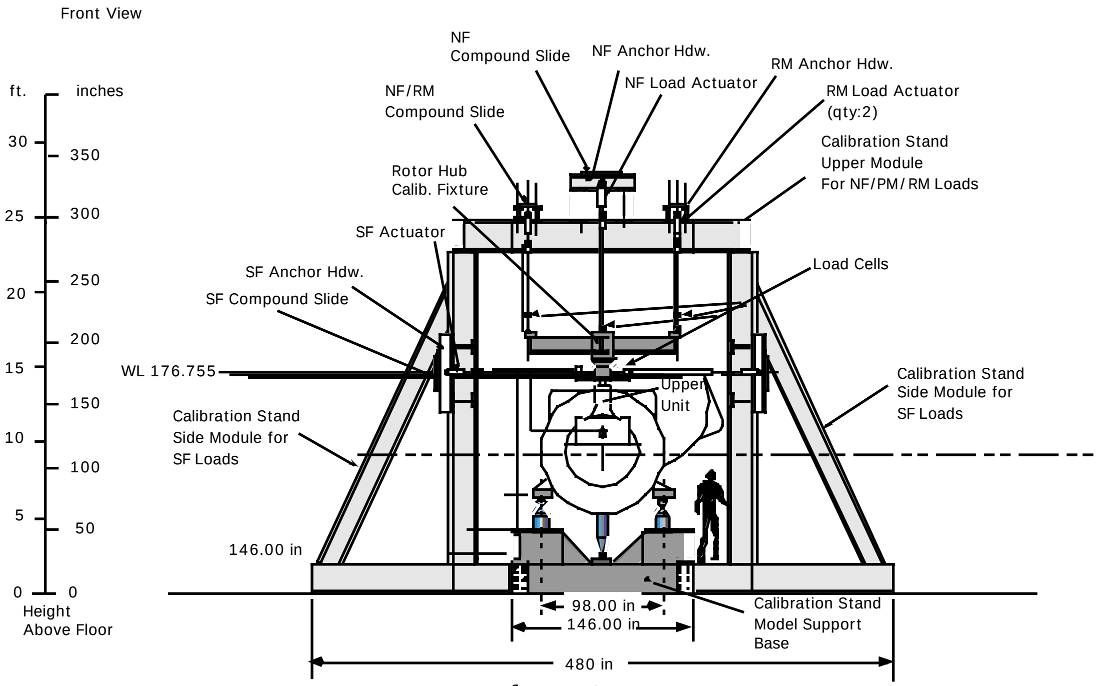
The bottom of the structural box is connected to all four vertical sides and also provides the structural support for the LRTA. The interface between the LRTA and the structural box is similar to the support system for a LRTA wind tunnel installation. Three struts are brought up from the bottom of the box to which the wind tunnel strut balls are secured. The LRTA is attached to the struts using a ball-socket interface (fig. 6).

A structural frame forms the top side of the structural box and provides the attachment point for the hydraulic load actuators, which provide for vertical loading into the LRTA rotor balance. The rig's top-side is approximately 160 inches above the balance moment center.

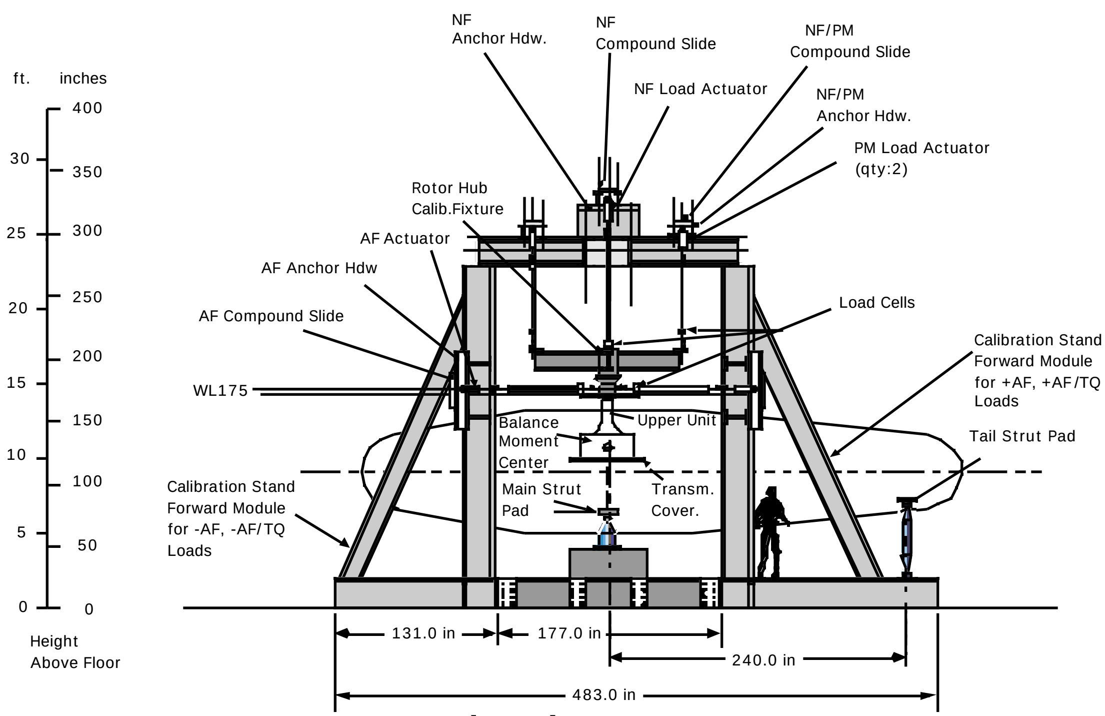
A previous calibration of a balance in the smaller Rotor Test Apparatus (RTA) was performed with the vertical sides of the structural frame/box being secured directly to the building floor, resulting is slight damage to the floor. Therefore, the LRTA calibration box frame is designed to be a self-contained system with respect to the balance loading. No structural connections are made between the box frame and the building's floor. The structural frame is placed upon 1-inch thick steel plates to distribute the weight across the building's floor.

<u>Structural frame</u>: W24x104 and W18x76 I-beams are used for the various sides, making up the calibration frame. Welding is used to connect the I-beams, making up each of the four vertical sides and the top. The calibration frame's design is modular in that the six sides of the box are bolted together at the

corner interfaces. Tolerance clearance in these interface connections is expected to be the major contributor to deflections in the calibration frame under loading.

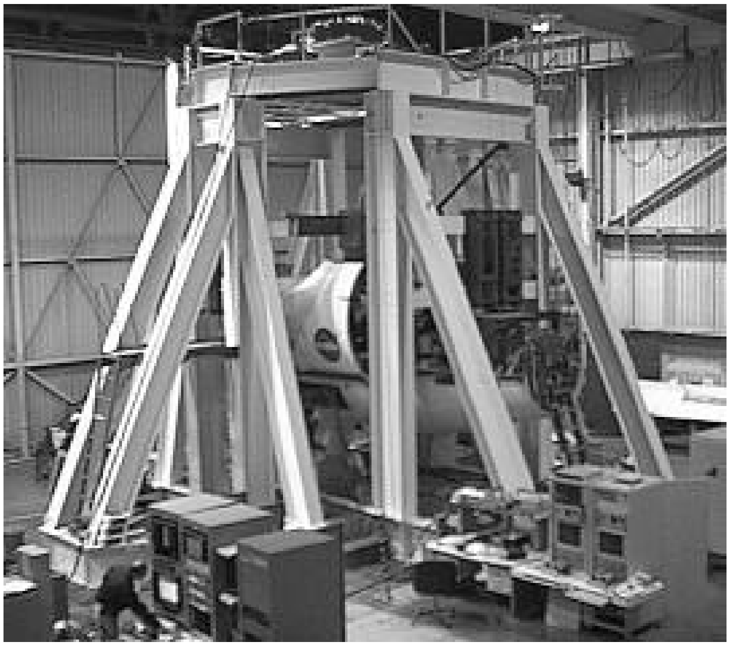


a: front view

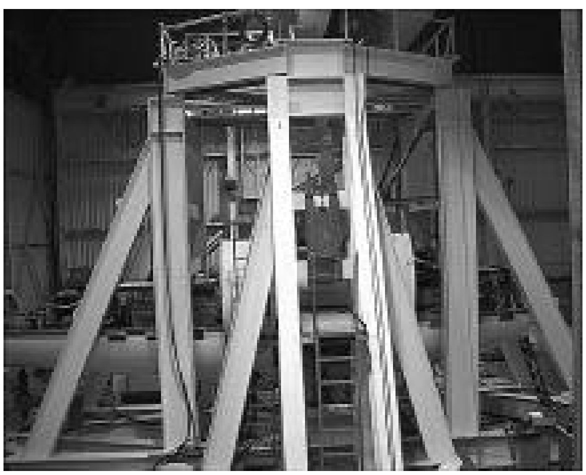


b: side view

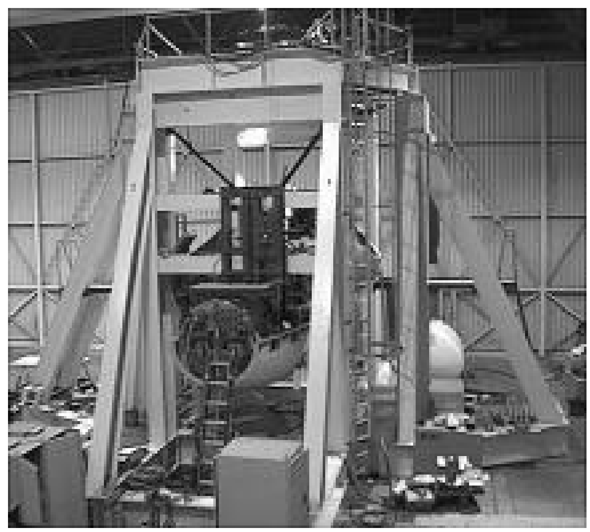
Figure 4: Schematic of the LRTA calibration rig



a. Front/right side view



b. Side view

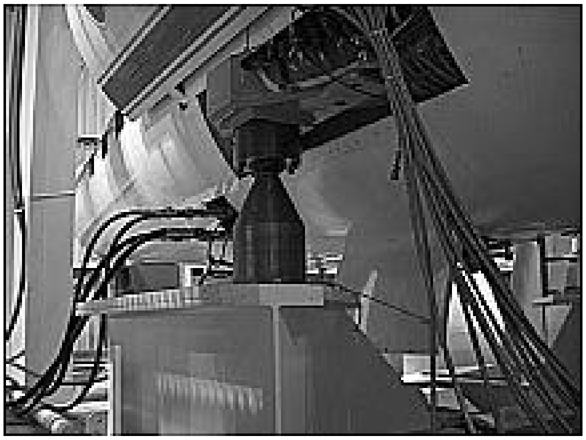


c. Front view

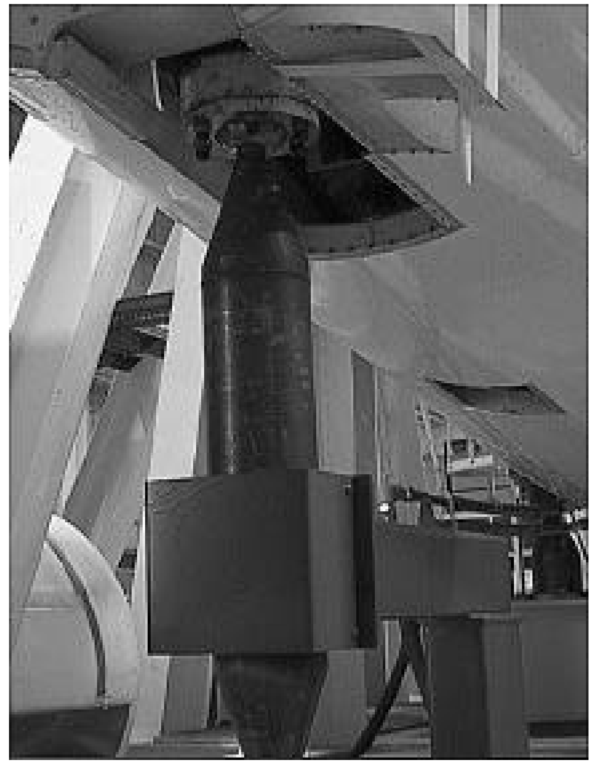
Figure 5: LRTA in calibration rig

Calibration Body

A calibration body is secured to the rotor shaft spline interface. The calibration body is designed for minimal deflections under the maximum hub loading to be applied to a rotor system, whose hub would be located at 60 inches above the balance moment center. The calibration body is modular in design and consists of three pieces: the lower cal body, the sprocket component, and the upper cal body.



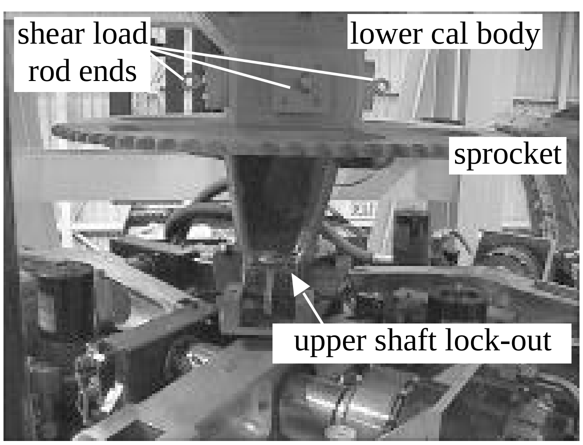
a. Main strut interface



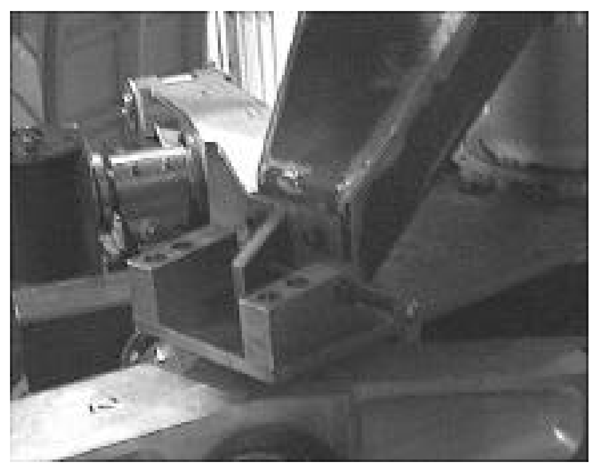
b. Tail strut interface

Figure 6: LRTA ball-socket interface support

The lower cal body contains the shaft spline interface. Rod ends are secured to the four faces of the lower cal body and form the attachment points for introducing the hub shear forces (AF and SF) into the balance calibration body (fig. 7).



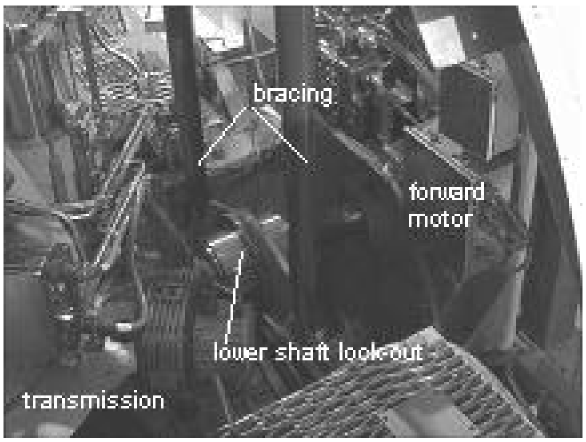
a. Sprocket and lock-out



b. Azimuth adjustment device

Figure 7: Lower calibration body with sprocket and upper shaft lock-out device

A 44-inch diameter sprocket is secured to the bottom of the cal body (fig. 7a). The sprocket and chain arrangement is used to introduce torque into the calibration body and shaft. This allows for the force loading to be applied tangentially to the sprocket at a known distance, being the sprocket's radius. Two separate shaft lock-out devices are used to prevent the shaft from rotating while applying loads to the calibration body. The upper shaft lock-out device, seen in fig. 7a, is used when applying all loads except shaft torque. The upper shaft lock-out device provides a connection between the sprocket and the LRTA upper housing such that all loads (including any residual torque loading due to potential misalignment of loading trees) are transferred from the shaft to the upper housing and into the rotor balance. Thus, the flex-coupling should not see any torque loading. The upper shaft lock-out device allows for limited rotation of the shaft prior to lock-out to ensure that the calibration body is aligned with the LRTA longitudinal axis (fig. 7b).



a. Shaft lock-out device

b. Shaft lock-out device bracing

Figure 8: Lower shaft lock-out device

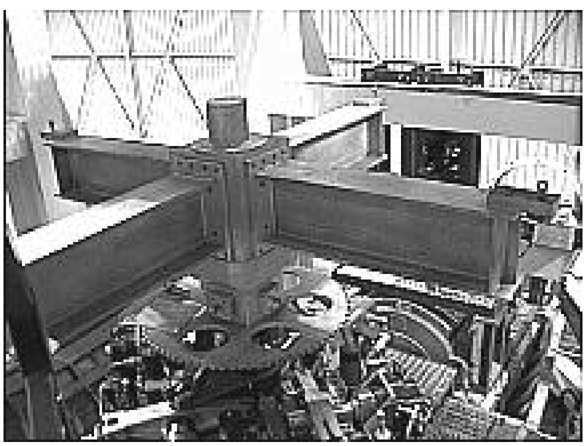


Figure 9: Upper calibration body

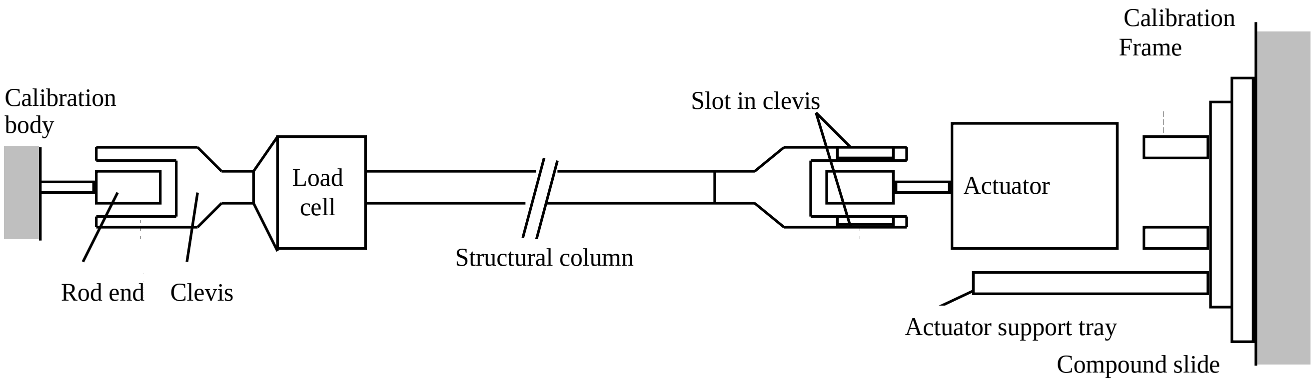
When applying torque to the shaft by means of the sprocket-chain arrangement, the upper shaft lock-out is removed and the lower shaft lock-out device is installed which locks out the transmission input shaft at the forward motor; see fig. 8. The lower shaft lock-out device allows for the transfer of the applied shaft torque into the instrumented shaft flex-coupling and into the transmission gear before the torque is counter-acted by the shaft lock-out against the calibration rig using the bracing seen in fig. 8b.

The upper cal body provides the attachment point for applying normal force loading. The crossbeam structure allows for applying a vertical load at a distance of five feet from the axis center and thus introducing a hub moment (fig. 9).

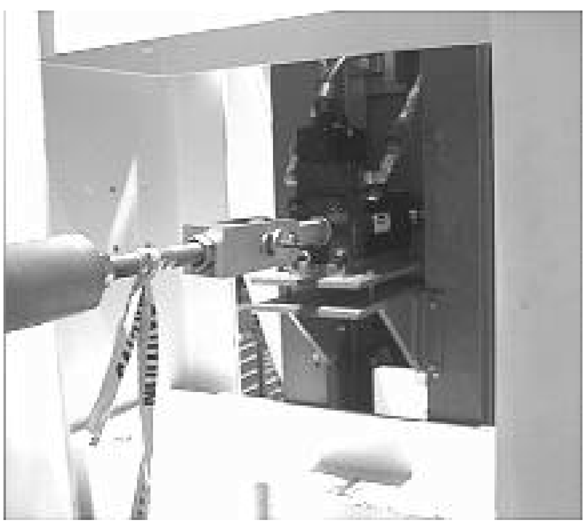
Load System

The load system consists of the loading tree, which provides the mechanical connection between the calibration frame and the calibration body, and the control system, which controls the loading applied to the balance. The loading tree is described first, followed by a discussion of the control system and its operation.

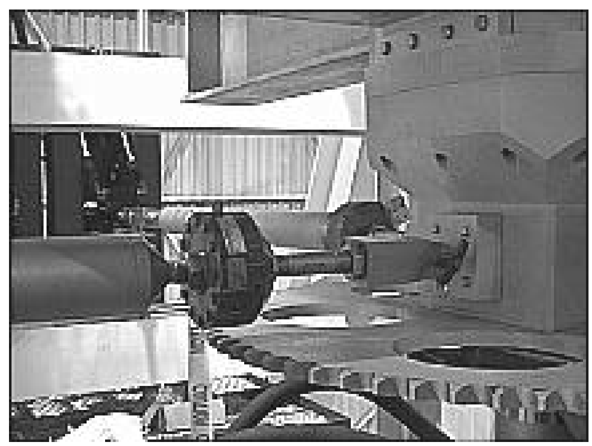
Loading trees: A total of eleven loading trees are used to apply loading to the balance. Each loading tree consists of a hydraulic actuator, a load cell, a structural column, and clevises and rod-ends for connecting the tree to the calibration frame and the balance calibration body (fig. 10a). The hydraulic actuator is located close to the calibration frame and its non-metric side is secured to a compound slide (fig. 4) to allow for accurate positioning of the actuator with respect to the balance calibration axis system. A clevis and rod-end interface is used between the actuator and the x-y table. The hydraulic actuators, which introduce AF, SF, and TQ loading into the balance calibration body, are supported to minimize the introduction of a vertical cross-component loading due to the weight of the actuator, which ranges from 50



a. Loading tree components



b. Calibration rig end, showing actuator



c. Calibration body end, showing load cell

Figure 10: Loading tree

to 75 pounds depending upon the actuator's load capacity (fig. 10a). A rod-end is installed into the actuator rod. A structural column is connected to the actuator rod-end by means of a pin and sliding clevis. A 3 inch long slot in this sliding clevis ensures that the actuator/load cell can be completely unloaded when desired. When the actuator rod is fully extended, the ball-lock pin is located at the center of the slot in the sliding clevis (fig. 10b). Thus, the loading tree can not be operated in a compression mode. All loading trees operate in a tension direction only. The structural column is threaded into a single-component Interface load cell. A clevis is secured to the metric side of the load cell. This clevis is connected with a pin to a rod-end, which is attached to the calibration body (fig. 10c). The load cell is located as close as possible to the balance calibration body and measures the applied loading. The clevis to rod-end connections at both ends of the loading tree minimize the potential of introducing any cross loading; that is, minimize the introduction of a load component which is in a plane perpendicular to the load cell's measurement direction.

Control system: The control system for applying balance loading utilizes a closed loop hydraulic system, which is controlled through software running on a stand-alone Programmable Logic Controller (PLC); fig. 11.

The applied loading, as measured from the load cell in the loading tree, is compared to the commanded loading. The difference between applied and commanded loading is used for adjusting the hydraulic pressure to the actuator in the considered loading tree. The GE-Logic Master language is used in programming the PLC.

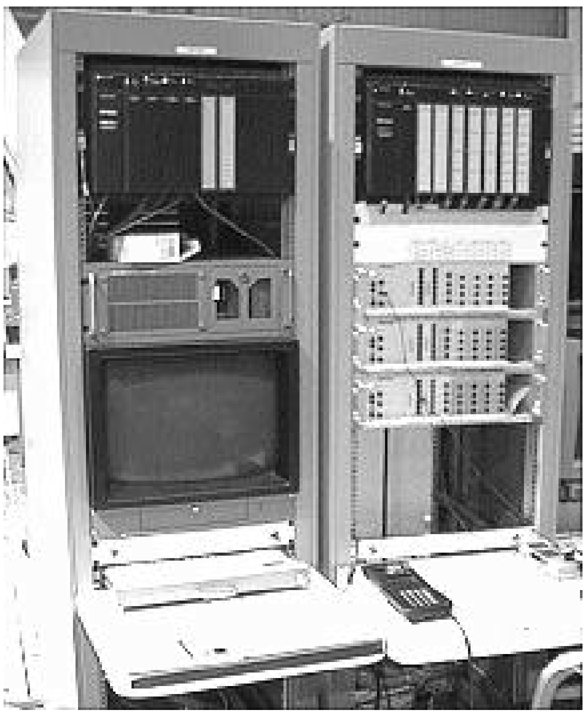


Figure 11: Hydraulic control system

The load cells are conditioned using MOOG power supplies/conditioners, which are part of the control system. Each MOOG power supply provides the excitation for up to two load cells. A six-wire system is used for the load cells, consisting of two wires for excitation voltages, two wires for signal out, and two wires for applying the rcal-resistor. There is a shield wire for each set of two wires. A relay at the control system console is activated by the PC-program to apply the rcal-resistor. The two rcal-wires allow for the rcal-resistor to be applied across positive power and positive signal at the load cell connector.

A stand-alone PC is used to provide the interface between the control system operator and the PLC, which controls the hydraulic pressure in the system. This PC allows for sending commands to the PLC and for displaying the measured loading as computed from the load cell data by the PLC. The load application control software on this PC allows for a semi-automatic loading of the balance and program control is through a Graphical User Interface (GUI). The software reads a load matrix from file into memory. The matrix columns represent the desired loading for each of the eleven loading trees and each row in the matrix represents a load point or condition. The control system software displays a four-by-eleven data table on the GUI-control window. The table columns represent the eleven loading trees. Table rows one and two are the previous and current desired load points, respectively, and row four represents the next desired load point. The third row shows the actual applied loading as measured by the load cells in the loading trees. This tabular display allows the operator to determine which load point in the overall load matrix has been selected and whether this desired load condition has been reached. The GUI window has UP and DOWN buttons, and a LOAD and STOP button. The UP/DOWN buttons allow the operator to scroll through the load matrix, stored in the software's memory using rows one, two, and four of the data table in the GUI-window. Pressing the LOAD button loads the desired loading, being row two of the data table, into the program variable, representing the commanded loading. This commanded loading is then downloaded to the PLC. The PLC software will adjust the hydraulic pressure to the actuators until the measured loading matches the commanded loading to within a pre-specified tolerance.

A STOP button is available on the GUI-window and represents a software panic button for the hydraulic actuator control system. Depressing the STOP button will send a command to the PLC to release the hydraulic pressure to the actuators and thus unload the balance.

Multiple safeguards are built into the hydraulic control system. Figure 12 provides a simplified schematic of the system in which the hydraulic system for one actuator is depicted. A pressure line runs from the main hydraulic supply reservoir through a 3-micron filter and through a check-valve into a hydraulic supply distribution manifold. A 1.5-gallon accumulator is used to minimize pressure fluctuations in this manifold. Four lines feed pressure to four separate pressure manifolds. A separate manifold is used for the shear force actuators (AF and SF), for the hub moment actuators (PM and RM), for the torque actuators (TQ), and for the normal force actuator (NF). A hydraulic pressure control valve and a pressure reducer are installed in the feed-lines to each of these four pressure manifolds. The pressure control valve allows only the specified pressure to be supplied to the considered hydraulic manifold regardless of the main hydraulic pump pressure. Each of the four manifolds has been equipped with a pressure switch, a pressure transducer, a pressure gage, and a pressure relief valve. If the pressure control valve fails, the pressure relief will operate and prevent the pressure from exceeding the set limit. If the pressure control valve and the pressure relief valve fail, the pressure high limit switch is triggered to shut off hydraulic supply to the whole balance calibration hydraulic control system. If all these three safeguards fail, the software program will trigger the hydraulic supply to be shut off when the manifold's pressure transducer reaches the preset pressure limit.

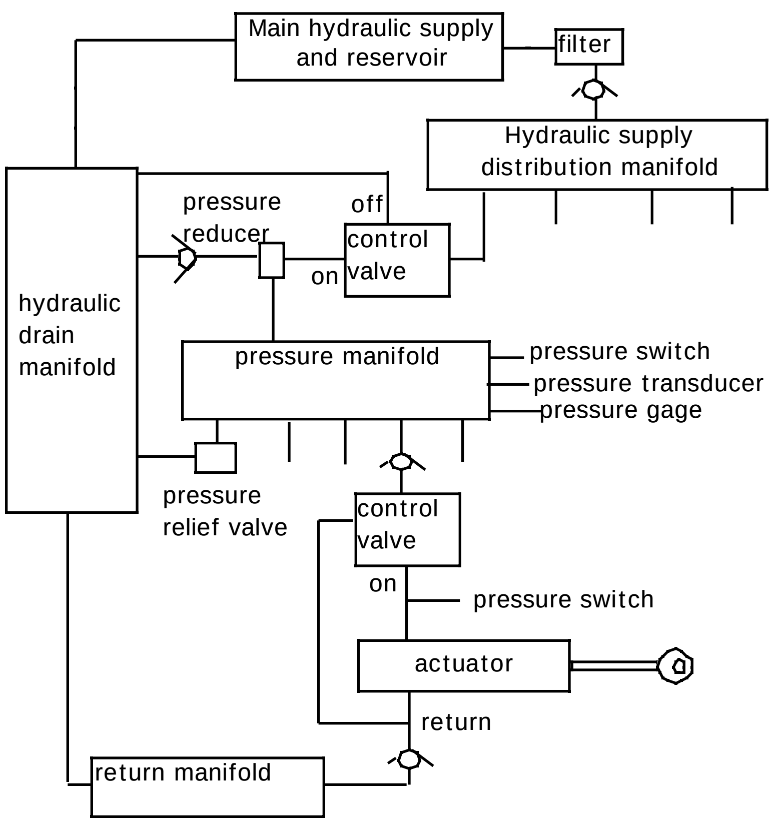


Fig. 12 Simplified schematic of hydraulic control system

The pressure from the manifold to each actuator in a loading tree is controlled by means of a separate servo valve. A pressure switch is installed between the servo valve and the actuator. This pressure switch is used as a diagnostic indicator by the control operator to ensure that pressure is available at the actuator.

The control software also contains safe guards in that if a loading is found to exceed a pre-specified limit, the system will command the servo valve to remove pressure to the actuator. The flow rate of the hydraulic fluid through the servo valves and into the hydraulic actuators is controlled to minimize the chance of overshooting the desired loading, which is especially critical when approaching the balance load limits such that the balance is not overloaded. The ramp signal is used for changing the hydraulic pressure in the loading tree's actuator.

Data Acquisition System

The data acquisition system, the acquired data, and the online data reduction program are described in this section.

Instrumentation: As mentioned above, the load cells are conditioned by the hydraulic control system and the load cell responses are used to control the pressure to the actuators and thus the loading applied to the LRTA rotor balance. The load cell excitation voltages and responses are also inputs to the data acquisition system.

All the Wheatstone bridges on the balance flexures are common powered. A six-wire system is used for each balance bridge; two wires provide excitation voltage to the bridge, two wires measure the bridge signal, and two wires are used for applying the rcal-resistor. There is a shield wire for each set of two wires. A relay box near the power supply allows for applying the rcal-resistor across positive power and positive signal at the balance connector. The wiring system duplicates the normal instrumentation setup used in the wind tunnels.

The voltages from the loading tree load cells and the Wheatstone bridges on the flexure posts of the rotor balance are acquired using three HP 34970A data acquisition/switch units (fig. 13). Each HP 34970A has three slots in its back panel, which allows for the insertion of different data acquisition boards. The HP 34901A 20 channel multiplexer boards are used. Two HP 34970A units contain three boards and one HP 34970A unit contains two boards. Both the output signal voltage and the bridge excitation voltage is acquired for each of the load cells and each of the balance/flex-coupling Wheatstone bridges. Data from the various thermocouples on the balance and the RTD's on the flex-coupling are also acquired.

The channels on the boards within the three HP 34970A units are grouped in a similar manner: response data on board 100, excitation data on board 200, and thermocouple data on board 300. HP-unit #1 acquires the data from the primary gage set and temperature readings from thermocouples located on the non-metric balance side. HP-unit #2 acquires the response data from the secondary gage set and temperature readings from thermocouples located on the metric side of the balance. HP-unit #3 acquires the response data from the load cells in the loading trees. A "commence data acquisition" command is sent to all three units such that within the internal clock interval of the HP-units, data acquisition is started at the same time for all three units. Each HP-data channel is sampled over two power cycles to obtain the 6-digit accuracy advertised for the HP 34970A units, while allowing for a reasonably fast update rate on the data acquisition computer. Sequential sampling over two power cycles of the 60+ channels on units one and two and 24 channels on unit three results in an actual data acquisition duration of approximately two seconds. Ideally, simultaneous data acquisition of all data channels is desired. The described system minimizes the effects on non-simultaneous data acquisition by appropriate distribution of data channels across the three HP 34907A units, starting the data acquisition on all three HP-units simultaneously, and acquiring all data within a 2 second interval.

Data acquisition program: A PC-computer, running Windows NT, is used for the data acquisition (fig 13). The main data acquisition program is written in Labview. Labview, version 5, provides a MATLAB-node for establishing an Application Program Interface (API) to Matlab with Labview functioning as the client and Matlab being the server. The Labview program provides communication between the PC and the HP 34970A data acquisition/switch units over a GBIP-interface. The Labview main program instructs the HP units to acquire the data and to store these data into the HP-unit's local memory buffer. The Labview program subsequently uploads these data to the PC and passes it on to various Matlab utilities for storage of the raw voltage data to file, for online data reduction, and for display of reduced data in table and graph format on the PC's monitor.

Control of the data acquisition process is through Graphical User Interface (GUI) windows (fig. 13). A Labview GUI window is used to initialize the HP-units, to initiate the MATLAB API, and to control the data acquisition rate. A MATLAB GUI window is used to control data storage to file and to select the manner in which acquired data are displayed in various tables and in plot format.

Figure 13: HP 34970A data acquisition / switch units and data acquisition computer

The Data Acquisition System (DAS) operator selects the time interval between subsequent data acquisition points, which can be displayed in a time trace plot format. This time trace plot allows the operator to monitor the balance response behavior during transition between two balance load conditions and to determine when a load condition has been stabilized. The operator has a store button, which when pressed, will send the next acquired data string to file.

The responses of the individual load cells in the loading trees and the balance bridge responses can be displayed in voltage or engineering unit data. The acquired/stored data can also be displayed in an X-Y plot format to aid the operator in evaluating the responses of the various balance components as a function of applied loading. The individual balance bridge voltages are combined into equivalent force and moment voltage data and these voltages are multiplied by theoretically derived conversion constants to obtain an initial estimate of the measured balance forces and moments in the balance axis system.

Calibration axis system: A calibration axis system is defined whose origin is located at the center of the cross-section at the top of the rotor shaft (fig. 2). The x-axis is defined to be parallel to the LRTA's longitudinal axis and is positive in the aft direction. The z-axis is defined to be along the shaft axis and is positive upwards. The y-axis is perpendicular to the x- and z-axis and is defined positive to the right as seen from a LRTA pilot's perspective.

The attachment points of the shear force loading (AF and SF) are located at 2.87-inches below the calibration axis origin and at a radial distance of 9.82-inches from the shaft axis. The attachment point of the normal force loading is on the z-axis at 8.05-inches above the calibration axis origin. The attachment points for the roll and pitch moment loading are at 29.19-inches above the calibration axis origin and a radial distance of 60.00-inches from the shaft axis. The sprocket, used for applying torque into the calibration body, is located 7.33-inches below the calibration axis origin and horizontal loading is applied at a radial distance of 22.2875-inches from the rotor shaft. The location of these attachment points was verified after component assembly.

Loading in calibration axis system: The load cell responses are converted to engineering units and the individual load cell force vectors are subsequently combined into the three forces and three moments in the calibration hub axis system. The balance loading is also transferred from the balance axis system into the loading in the calibration hub axis system. The derived forces and moments in the calibration hub axis system, as obtained from the load cells and from the two balance gage sets, are displayed in tabular format on the DAS monitor, allowing the operator to compare the computed loading from these three separate measurement systems. This comparison provides an additional safeguard to ensure that the LRTA rotor balance is not overloaded.

Balance Calibration Process

The calibration process consists of the initial system verification, the data acquisition and online data reduction (described above), and off-line balance data reduction analysis to obtain the balance calibration matrix. The system verification, flex-coupling loading, calibration load envelope, and off-line data reduction and analysis are discussed briefly below.

System verification: The overall hydraulic control system operation is verified in a separate test facility which allows for operating one loading tree sub system at a time, although all actuators are hooked up to the hydraulic control system. This test facility allows for the in-line mounting of a hydraulic actuator, its corresponding load cell to be used in the loading tree, and a master load cell. The actuator/load cell is exercised between zero and the maximum loading to be applied by the loading tree in the actual balance calibration. This operation is repeated for each hydraulic actuator/load cell assembly for each of the eleven loading trees to verify the hydraulic control system operation.

Prior to installation into this hydraulic test rig, the two load cells are mounted in series and are check-loaded to 5,000 lbs using five 1,000 lbs lead weights. Load cell data are acquired through the data acquisition system to verify the operation of the overall system.

After system verification the actuator/load cell is installed into the loading tree and the assembly is installed into the calibration rig.

Flex-coupling loading: The torque and residual thrust components on the flex-coupling have been calibrated to maximum load capacity in an independent calibration facility. Interactions of torque on residual thrust were seen, but no interaction of thrust onto torque. This is due to the large discrepancy in load capacity between the torque and residual thrust components.

When calibrating the rotor balance yaw moment, YM, the shaft is locked out against the upper housing such that all shaft torque (or shaft yaw moment) is transferred to the upper housing and therefore the flex-coupling does not see a torque loading. The flex-coupling torque, TQ, is monitored to ensure that this is indeed the case.

For the check-loading of the flex-coupling torque, TQ, the input shaft into the LRTA transmission is locked out against the calibration rig. Torque is applied to the calibration body, which is secured to the top of the rotor shaft. The sum of the rotor balance yaw moment, YM, and the flex-coupling torque, TQ, should equal the applied moment or torque to the rotor shaft.

Load envelope: The desired calibration loading is initially defined as the three forces and three moments in the calibration axis system. The corresponding loading, to be applied through each of the eleven loading trees to obtain these forces and moments, is subsequently derived. Since the calibration effort requires several weeks, the calibration load envelope is sub-divided into several load sequences. For each load sequence, an input file to the hydraulic control system is created which defines the desired loading on the eleven hydraulic actuators for each load point in the load sequence.

The calibration load envelope consists of single-component and two- and three-component loading in the calibration axis system. Normal force loading is applied through the calibration axis system origin, whereas the offset of the axial force and side force load point with respect to the origin is minimal. Thus single-component force loading can be obtained. However, single-component or pure moments in the calibration axis system can not be obtained in the LRTA calibration rig since moments are obtained by force loading at some distance from the calibration axis system's origin. Therefore, moment loading is always in combination with a force loading. Therefore, simultaneous loading of two balance moment components results in a minimum of three balance components being loaded: two moments and one force component. The defined calibration load envelope consist of some 1200 load points, containing single-component loading and all possible combinations of two balance components being loaded simultaneously so as to be able to compute all coefficients in the balance response math model (see below).

Offline balance data reduction: Separate software is used to perform the offline data reduction and the subsequent data analysis. The off-line data reduction, which is described in this sub-section, computes the applied loading in the balance axis system and derives the equivalent force/moment response data for the two balance gage sets for each load sequence. This software combines these loading and balance responses from each load sequence into one large calibration database. The data analysis program is used to obtain the balance calibration matrix from analysis of the calibration database as described in the next sub-section.

The responses of the eleven load cells are converted to engineering unit data and the applied loading in the balance axis system is subsequently determined. The applied normal force loading is seen by both the rotor balance (NF-component) and the residual thrust, TH, on the flex-coupling. The loading seen by the flex-coupling residual thrust is typically 1.5 to 2% of the applied normal force loading. Since the flex-coupling thrust component is calibrated separately, the loading seen by the rotor balance NF-component is defined to be (Applied_loading - TH) lbs.

The individual flexure readings for a balance gage set are combined into equivalent three force and three moment readings, as shown below:

$$
\begin{array}{ll}
\text{axial force:} & V_{AF} = AF000 + AF090 + AF180 + AF270 \\
\text{side force:} & V_{SF} = SF000 + SF090 + SF180 + SF270 \\
\text{normal force:} & V_{NF} = NF000 + NF090 + NF180 + NF270 \\
\text{roll moment:} & V_{RM} = NF270 - NF090 \\
\text{pitch moment:} & V_{PM} = NF180 - NF000 \\
\text{yaw moment:} & V_{YM} = -AF000 + SF090 + AF180 - SF270
\end{array}
\tag{1}
$$

The entries in the right hand side of eq. (1) represent the individual Wheatstone bridge readings, representative of the three mutual perpendicular forces (AF-axial, SF-side, NF-normal force) at a particular flexure, where the extension xxx represents the azimuth location of the flexure.

The variables in the left and right hand sides of eq. (1) have the units of voltage. During both the balance calibration effort and the wind tunnel test, the individual flexure force readings from the Wheatstone bridges are obtained (RHS of eq. (1)), and combined as per eq. (1).

Data analysis: The calibration database forms the input to the off-line balance calibration data analysis software (ref. 1), which performs the curve fit to obtain the coefficients in the balance response math model. This balance response math model for the three forces and three moments follows the standard model for internal strain gage balances as recommended by the Ground Testing Technical Committee (GTTC) of the American Institute of Aeronautics and Astronautics (AIAA) (refs. 2-3). The recommended model is defined by the following polynomial math model for describing the balance response for gage i, V_i, to balance loading, L_j, j=1,...,n, where n is the number of independent balance load terms (ref. 1-3):

$$
V_i = V_{o,i} + \sum_{j=1}^{n} a_{ij}L_j + \sum_{j=1}^{n} b_{ij}|L_j| + \sum_{j=1}^{n}\sum_{k=j}^{n} c_{ijk}L_jL_k + \sum_{j=1}^{n}\sum_{k=j+1}^{n} d_{ijk}|L_j|L_k + \sum_{j=1}^{n}\sum_{k=j}^{n} e_{ijk}L_j|L_k| +
$$

$$
\sum_{j=1}^{n}\sum_{k=j+1}^{n} f_{ijk}|L_j||L_k| + \sum_{j=1}^{n} g_{ij}L_j^3 + \sum_{j=1}^{n} h_{ij}|L_j|^3 \tag{2}
$$

The off-line data analysis program performs a global regression analysis on the calibration database to obtain the balance calibration matrix, which contains the conversion constants and interaction coefficients (ref. 1).

The load envelope with respect to the calibration axis system is defined such that all forces and moments are loaded in a systematic manner and all possible two-component balance loading L_jL_k shown in eq. (2)

are applied. The applied loading is subsequently transferred to the balance axis system prior to performing a global regression analysis to obtain the coefficients in eq. (2). Defining the load envelope in this manner ensures that the balance calibration loading conforms to the loading introduced to the balance during a typical rotor wind tunnel test.

Concluding Remarks

To enable moderate-to-large helicopter rotor system testing at NASA Ames Research Center, NASA and the U.S. Army are developing the Large Rotor Test Apparatus (LRTA). The LRTA's rotor balance allows for operating helicopter rotors at thrusts up to 52,000 pounds. A description of the LRTA and the rotor balance are provided.

The physical design of the calibration rig for the LRTA's multi-component balance is described. Hydraulic actuators with in-line load cells are used to apply the calibration loading. The hydraulic control system provides independent control of each of eleven load actuators, thus allowing for single- and multi-component calibration loading of the rotor balance. The hydraulic control system utilizes the readings from the load cells to adjust the hydraulic pressure to the actuators to apply the desired loading. The control software allows for input of a calibration load envelope file, and facilitates the setup on pre-specified balance load conditions. Multiple safeguards (mechanical and software) are implemented to ensure that the loading will not exceed the balance capacity.

A separate data acquisition system is used to determine the applied calibration loading measured by the load cells and to measure the balance gage response.

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